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SENSITIVITY OF MUZZLE VELOCITY REPEATABILITY TO VARIATIONS IN INITIAL CONDITIONS

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13. ABSTRACT *(Maximum 200 words)*

Interior ballistic data from 20 tests with a 30-mm regenerative liquid propellant gun (RLPG) are examined. The tests are divided into four groups, with five tests in each group. The particular RLPG, referred to as Concept VI, is based on an annular-sheet-type of injector. The propellants used for the tests were liquid gun propellant (LGP) 1845 and LGP 1846. The mean muzzle velocity and the standard deviation for the first three groups was 855 ms (1.0%), 903 ms (1.9%), and 867 ms (2.1%). For groups 2 to 4, the igniter charge was increased from 3.0 g to 3.5 g. The significant increase in velocity for the second group of tests could not be explained by the small increase in the igniter charge. The increase in velocity, as well as the large standard deviations, is presently under study. Interestingly, the fourth test group, in which the initial conditions were more closely controlled, yielded a mean muzzle velocity of 873 ms with a standard deviation of 0.83%. Because of the large variations in the first three group of tests, especially when compared with other RLPG firing test data, a study of some of the parameters was undertaken which might influence the muzzle velocity.

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1. INTRODUCTION

A 30-mm regenerative liquid propellant gun (RLPG) was used to investigate variations in both the initial conditions and the early time-dependent parameters which might influence the muzzle velocity. The gun is based on a design which has been referred to as Concept VI and has been described elsewhere (Mandzy, Cushman, and Magoon 1984a, 1984b; Reever 1984; Pate and Magoon 1985; Magoon et al. 1985; Watson et al. 1985, 1986; Watson and Knapton 1987). Interest in examining the start-up conditions was based on some interior ballistic reproducibility data which was reported at the 22nd JANNAF Combustion Meeting (Magoon et al. 1985). In this earlier paper, it was shown that the muzzle velocity for the first group of tests performed with the 30-mm was poor, especially when compared with data obtained from similar regenerative fixtures. The reasons for the poor reproducibility were not identified. It was therefore considered important to further examine the parameters which might influence the poor reproducibility. The propellants tested included Otto-II, a naval torpedo fuel, and the hydroxylammonium nitrate-based liquid gun propellants (LGP) 1845 and 1846. A summary of the thermochemical properties of the propellants and the earlier reproducibility data are repeated here for convenience.

1.1 Propellant. A summary of the thermochemical properties are given in Table 1.

Table 1. Properties of the Liquid Propellants Used in the 30-mm Tests[a]

LP	Fuel, Name	Fuel, wt%	HAN, wt%	Water, wt%	Density, g/cm^3	Impetus, J/g	Flame Temperature, K	γ
1845	TEAN	20.0	63.2	16.8	1.45	934	2,592	1.218
1846	TEAN	19.2	60.8	20.0	1.43	898	2,469	1.223
Otto-II[b]					1.23	866	1,986	1.266

[a] Loading Density = 0.2 g/cm^3 (Freedman 1987).
[b] Composition of Otto-II: 1, 2 dinitroxypropane 76%, di-N-butyl sebacate 22.5%, 2 nitrodiphenylamine 1.5%.

1.2 Summary of Earlier Reproducibility Data. The 30-mm was tested first at the General Electric (GE) test facility using Otto-II (Reever 1984; Pate and Magoon 1985; Magoon et al. 1985). It was also tested at the U.S. Army Ballistic Research Laboratory (BRL), Aberdeen

Proving Ground, MD, using the LGPs 1845 and 1846 (Magoon et al. 1985; Watson et al. 1985, 1986; Watson and Knapton 1987). The results of the earlier reproducibility tests are summarized in Table 2. These tests include the first group of reproducibility test firings with the 30-mm Concept VI using Otto-II.

The tests with Otto-II LGP 1845 and LGP 1846 were all fired with a 2/3 charge and a relatively thin injection sheet. The thin injection sheet resulted in a relatively low ballistic performance, a result that could have been improved if the sheet thickness had been increased. The reproducibility of the tests with Otto-II gave a standard deviation of 1.6%. The initial position of the projectile was varied during these tests and therefore may have contributed to the poor reproducibility. The reproducibility of the tests with 1845 was about the same. For these tests, an attempt was made to initially seat the projectile in the same position. If the apparent outlier (Identification No. 364-046) is omitted, then the standard deviation becomes 0.80%. Furthermore, an inspection of the data suggests that the data may be divided into two groups with mean velocities of 1,005 ms and 1,019 ms. The respective standard deviation of the two groups is 0.05% and 0.24%. The reason for the apparent grouping of the data was not known when the data was presented at the 22nd JANNAF Combustion Meeting (Magoon et al. 1985). The lack of a satisfying explanation for the two groups of data was the basis for the present study.

2. APPROACH

Problems in interior ballistics are often related to abnormal ignition and/or combustion, which may depend on the initial conditions and which may show up in the early pressure rise in the chamber, or in the early projectile motion. We therefore decided it might be instructive to examine both the initial conditions and the early start-up conditions in some detail.

The initial conditions that were examined included the igniter charge, two methods for seating the projectile, and the overall assembly procedures. The evaluation of the igniter charge depended on performing some reproducibility tests in closed chambers with volumes similar to the chamber volume of the RLPG. The two methods for seating the projectile consisted of a simple hammer approach and a screw and clamp method for pressing the projectile into the engraving region. Additionally, two gun tubes were used. One gun tube showed some evidence of erosion; the other tube was new.

Table 2. Summary of Earlier Reproducibility Tests With the 30-mm, Concept VI, Using a 2/3 Charge

Identification No.	LP	Pressure[a] J120, MPa	C30, MPa	A90, MPa	LP, MPa	Velocity, m/s
335:14	Otto-II	164	192	174	—	939
336:15	Otto-II	—	—	—	—	950
342:13	Otto-II	144	180	179	—	930
343:12	Otto-II	179	197	168	—	965
Mean	Otto-II	162	190	174	—	9[illegible]6[b]
Std/Dev/Mean	(%)					1.6
364-032	1845	177	190	197	—	1,020
364-033	1845	167	181	181	—	1,005
364-034	1845	177	190	191	—	1,005
364-035	1845	182	186	194	—	1,020
364-041	1845	171	189	192	227	1,018
364-042	1845	182	181	195	202	1,021
364-043	1845	166	177	184	—	1,005
364-044	1845	—	—	—	—	1,004
364-046	1845	169	178	186	—	973.5
Mean	1845	174	184	190		1,008[c]
Std/Dev/Mean	(%)	3.7	2.9	3.0		1.5
12	1846	190	195	205	—	1,023
13	1846	184	184	190	285	1,009
27	1846	213	205	231	—	1,011
Mean	1846	196	195	209	—	1,014[c]

[a]J120 gage located 12 mm forward of the initial position of the piston face and gages C30 and A90 gages located, respectively, 21 mm and 36 mm to the rear of the initial position of the piston face. The error in the pressure readings, especially for the gages in the C and A plane, may be as high as 10%.
[b]Tested at GE. Initial position of projectile varied.
[c]Tested at BRL.

The early start-up conditions that were studied included the reproducibility of the igniter output and the early pressure and projectile start-up characteristics. The pressure and projectile start-up characteristics are based on the interior ballistic data which were recorded using the methods described in Magoon et al. (1985).

The early start-up parameters included shot start pressure (P1), a chamber pressure (P2) arbitrarily measured after the projectile had been displaced about 5.4 mm, time between P1 and P2, maximum pressure in the igniter chamber, an igniter rise time, igniter rise rate, the piston velocity during igniter venting, and the maximum piston velocity.

3. EXPERIMENTAL

3.1 Igniter. The igniter device consists of an M52A3B1 initiator and either 3.0 g or 3.5 g of IMR 4350. The principal ingredient in the M52A3B1 is lead styphnate. IMR 4350 is a single base extruded propellant normally used in small arms. Volume of the igniter cavity is 6.8 cm^3, and the limiting vent orifice diameter into the larger closed chamber, or the gun fixture, is 3.86 mm.

The thermochemistry of the solid propellant igniter components, IMR 4350 and M52 primer, are summarized in Table 3. Two examples are included representing loading densities of 0.0280 and 0.4663 g/cm^3. The first loading density example represents the pressure one would expect to obtain in the RLPG combustion chamber (volume equal to 95 cm^3) with the IMR 4350 booster charge. The second represents the pressure expected in the igniter chamber volume, 6.8 cm^3.

3.2 Closed Chambers. The ignition and combustion of the igniter propellant were studied using two different closed chambers. Pressures were measured in both chambers. Importantly, the length to diameter ratio (L/D) of the first chamber was 1.5, and, therefore, heat losses (Klingenberg et al. 1987) were probably not important (<10%). The second chamber consisted of the 30-mm gun chamber. In this chamber, the L/D was about 0.3 and may have resulted in significant heat losses. As a result, the maximum pressures were considerably lower than the pressures recorded in the first chamber. The 6.8 cm^3 igniter chamber was used in both RLPG combustion chambers.

3.3 The 30-mm RLPG Concept. A description of the Concept VI RLPG is given in Mandzy, Cushman, and Magoon (1984a, 1984b); Reever (1984); Pate and Magoon (1985); Magoon et al. (1985); Watson et al. (1985, 1986); and Watson and Knapton (1987). The following briefly describes the operation of the fixture. Propellant is injected into the

Table 3. Thermochemistry of the Igniter Charge Used in the Closed Chamber and Gun Tests (Freedman 1987)

Component	Loading Density, g/cm^3	Volume, cm^3	Flame Temperature, K	Impetus, J/g	Pressure, MPa
IMR 4350 3.0 g	0.0280	95.0	2,875	1,003	28.98
M52 and 3.0 g IMR	0.4663	6.8	2,884	974	777

combustion chamber in the form of an annular sheet. An illustration of the basic concept showing both the chamber and LP reservoir sections is given in Figure 1. In the upper half of the figure, the piston is in the forward position prior to firing. The lower half of the figure shows the piston in the rear position at the end of firing. The piston is a thin shell cylinder supported from deformation by a lubricating film and the chamber wall. At ignition, the pressure developed by the igniter in the combustion chamber forces the injection piston to the rear. Due to the differential area of the injection piston, the pressure in the reservoir is higher than the combustion chamber. As a result, LP is forced through the annulus formed by the outside of the control rod, or center bolt, and the inner diameter of the piston. The injected propellant then enters the combustion chamber. The instantaneous injection area is controlled by contours on the control rod. Initially, the area is sealed preventing leakage of LP into the chamber and allowing for the prepressurization of the LP reservoir. For the tests reported here, the initial prepressurization of the LP was 7.0 MPa. As the injection piston is displaced to the rear, the injection area rapidly increases, permitting an increase in the mass injection rate. Maximum injection area is reached at the end of the first or starting taper on the control rod. Motion of the injection piston is retarded towards the end of its stroke by the rear taper on the control rod.

3.4 Temperature Measurement. Temperatures were measured using a gage, referred to as an emission gage, which has been described by Klingenberg (1985). A brief description on the use of this device is given in this section. First, an optical pyrometer is calibrated using a calibrated tungsten lamp. The lamp used was a General Electric lamp with a tungsten ribbon filament with a nominal rating of 30 A at 6 V. The lamp was calibrated at the National

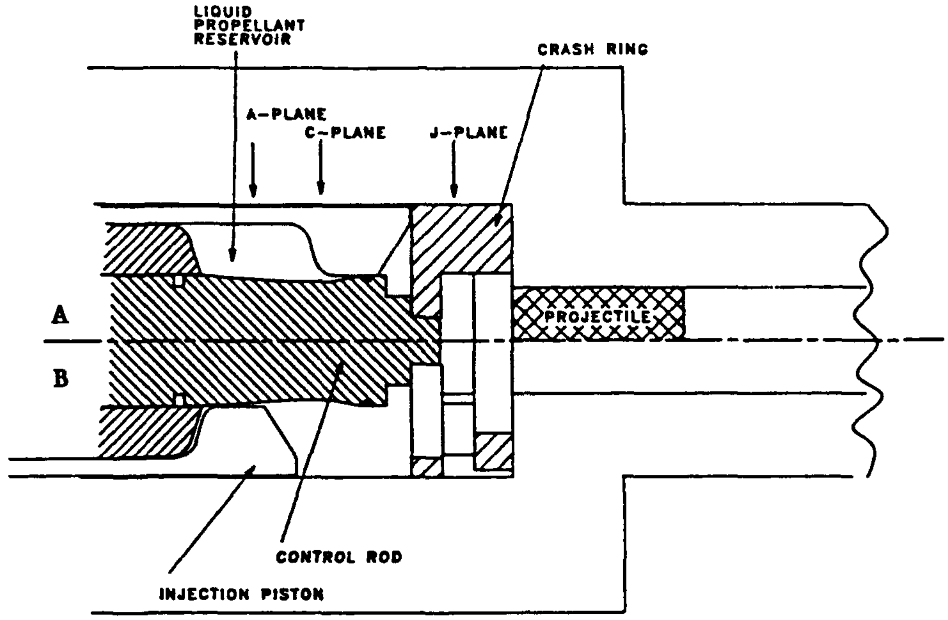

Figure 1. Schematic of the 30-mm, Concept VI, Regenerative Liquid Propellant Gun.

Institute of Standards and Technology from 1,173 K (12.37 A) to 2,573 K (42.55 A). A description on the use of this lamp is given by Kostkowski and Lee (1968). The lamp is calibrated in terms of a brightness temperature, defined as the temperature of a blackbody which has the same spectral radiance at a given wavelength as the unknown radiation source. The radiation from the lamp and the unknown source is detected with a photomultiplier (150 CVP/177) after passing through a narrow band filter (647.1 nm) and a diffuser. For calibration purposes, a chopper is used to conveniently detect the signal. Purpose of the diffuser is to generate a radiation source which approaches the random radiation emission associated with the actual test. The response of the photomultplier, in volts, is recorded as a function of current through the tungsten filament. A table of brightness temperature vs. both current and the response of the photomultiplier can then be constructed, which provides a basis for fitting the tungsten brightness temperature and the photomultiplier response to a suitable function. Two functions were investigated—a logarithmic and a second degree power function. It was found that the power function gave a better fit to the data and was therefore used in converting the test data to a brightness temperature (by multiplying the test data with the generated calibration function using an on-line ballistic data acquisition system).

4. RESULTS

The results are divided into three sections: a summary of the closed chamber tests on the reproducibility of the igniter parameters; a summary of the parametric study on the 30-mm start-up characteristics; and the results of the assembly procedures for the 30-mm, which includes the two different methods for seating the projectile.

4.1 Igniter Tests. The 6.8-cm^3 igniter chamber was tested in both closed chambers. The results are summarized in Tables 4 and 5. In these tables, the A, B, and C under the igniter column refer to the type of confinement of the IMR powder used in the 6.8-cm^3 chamber. In the A configuration, a portion of the powder adjacent to the M52A3B1 is confined in a paper straw. In the B and C configurations, a slightly larger diameter plastic straw was used which allowed more propellant to be directly in line with the M52A3B1. The C configuration had 3.5 g of IMR, whereas A and B configurations used 3.0 g. Significantly, as shown in Table 4, the B configuration yielded improved reproducibility for the recorded maximum pressures.

Despite the increased charge used in the second chamber (Table 5), the recorded maximum pressures were significantly lower than the maximum pressures recorded in the first chamber, a result, as pointed out previously, of the low L/D of the chamber and the postulated high heat loss.

Based on the maximum pressure data summarized in Table 3, an estimate of the igniter charge burned in the small igniter chamber may be made and, by comparison with the pressure-time data, an estimate of the unburned mass flux into the larger chamber may be calculated. Assume that no gas is vented from the igniter chamber during the rise to maximum pressure and that there are no heat losses. Then the mass of propellant burned in the igniter chamber is approximately proportional to the ratio of the measured pressure and the theoretical pressure. For configuration B, and based on a loading density of 0.466 g/cm^3, the comparison between the theoretical pressure from Table 3 and the observed pressure indicated that about 0.55 g of solid propellant actually burned in the igniter chamber while the remainder vented into the larger chamber (see Table 6). Examining the pressure-time data (Klingenberg 1985) or simply taking the 10 to 90% rise time given in Table 4 gives an approximate unburned mass flux, for configuration B, into the larger chamber of

Table 4. Summary of Experimental Igniter Results for the 106-cm^3 Closed Chamber

Igniter	No. of Tests	Mean Maximum Pressure: Igniter Chamber, MPa	Standard Deviation, %	106-cm^3 Chamber, MPa	Standard Deviation, %	Rise Time, 10 to 90%: Mean, ms	Standard Deviation, %
M52	1	10.6	—	1.1	—	—	—
A. M52 and 3.0 g IMR	6	181	15.2	16.8	3.1	1.37	14.4
B. M52 and 3.0 g IMR	9	141.8	9.1	17.3	7.8	1.60	23.1
C. M52 and 3.5 g IMR	2	(not measured)	—	21.5	—	—	—

Note: The loading densities, neglecting the M52A3B1 and assuming all of the propellant is displaced into the larger chamber, were 0.0266 g/cm^3 and 0.0310 g/cm^3 for, respectively, the igniter configurations A or B and C.

Table 5. Summary of Experimental Igniter Results for the 106-cm^3, 30-mm Closed Chamber

Igniter	No. of Tests	Maximum Pressure, MPa	Standard Deviation, %	Maximum Temperature, K	Standard Deviation, %
C. M52 and 3.5 g IMR	6	13.3	3.0	2527	5.8

Note: The loading density was 0.0325 g/cm^3. The igniter chamber pressure was not measured in these tests.

$2.45/(0.0016 \times 3.14 \times 3.86^2/4) = 131$ g/mm^{2}s. Similarly, for the A configuration, the approximate unburned mass flux = 143 g/mm^{2}s.

Additionally, an estimate of the total heat loss may be determined by comparing the experimentally measured pressures with the theoretical pressures. The results are summarized in Table 7.

The recorded maximum chamber temperature (Table 5) of 2,527 K is 12% lower than the theoretical value (Table 3). A comparison of the maximum chamber pressure (Table 3) with the theoretical pressure would suggest a much lower value for the measured temperature.

Table 6. Estimate of Propellant Burned in the Igniter Chamber and Unburned Propellant Which Vents Into the Gun Chamber

Igniter Configuration	Loading Density of IMR, g/cm^3	Mass of IMR Charge, g	Pressure		Estimate of SP	
			Experimental, MPa	Theoretical, MPa	Burned in 6.8 cc Chamber, g	Vented in to 106 cc Chamber, g
B. M52 and 3.0 g IMR	0.441	3.0	142	777	0.55	2.45
A. M52 and 3.0 g IMR	0.441	3.0	181	777	0.70	2.30

Note: The experimental pressure is taken from Table 3, and the theoretical pressure is extrapolated linearly from Table 1.

Table 7. Estimate of Heat Loss From the Burning of the Propellant in the Igniter and the Larger Chamber

Igniter Configuration	Loading Density, g/cm^3	Mass of IMR Charge, g	Pressure		Estimate of Heat Loss During the Combustion in the Two Chambers, %
			Experimental, MPa	Theoretical, MPa	
Chamber No. 1					
B	0.0281	3.0	17.3	28.8	39.9
A	0.0281	3.0	16.8	28.8	41.7
C	0.0325	3.5	21.5	32.9	34.6
Chamber No. 2					
C	0.0325	3.5	13.3	32.9	59.6

The ratio of the measured pressure and the theoretical pressure (taken from Table 6) suggests a heat loss of over 30% for Chamber 1 and a much larger heat loss for Chamber 2. This large heat loss is not considered unreasonable since the igniter gases must pass through a long, narrow vent before entering the RLPG combustion chamber.

4.2 The 30-mm Start-up Characteristics. The results of an evaluation of the start-up parameters are summarized in Tables 8 and 9.

The tests listed as Test Series 1 and 2 are one-third charge firings. The propellant charge was 80 cm^3 of LGP 1846. The projectile mass was 287 g nominal, and all projectiles were installed using the hammer technique.

The summary in Tables 8 and 9 of the various start-up parameters, aside from the maximum chamber pressure, showed no correlation with muzzle velocity. This lack of dependence raised questions on the overall experimental approach, including details of the assembly procedures.

4.3 Projectile Seating Methods. Two five-round comparison test series were performed. In the first test series, Series 3 (Table 10), the projectile was seated using one of two methods. A hammer was used for the first method, and a clamp and screw were used for the second method. The hammer method consisted simply of hammering the projectile into the engraving band. The clamp and screw method provided approach for forcing the projectile into the engraving band. In both cases, the projectile was displaced to the same position (i.e., flush with the end of the barrel).

The second test series, Series 4, used only the screw and clamp method. The conditions for the second test series also included paying closer attention to chamber assembly details than normally done in the earlier tests. These details included, for each test, the same orientation of the piston, transducer block, crash ring, and the same volume of grease used between the piston wall and the chamber. The results are summarized in Table 10 for Test Series 4. The tests were all fired from a new gun tube (starting with I.D. 68). The liquid propellant charge was a 1/3 charge (80 cm^3) of 1845 using an igniter charge of 3.5 g of IMR 4350. The nominal projectile weight was 287 g.

The results from Test Series 3 did not indicate that either method for seating the projectile improved muzzle velocity reproducibility. The earlier test series showed that with the hammer technique, a reproducibility of 1.0 to 1.9% was achievable. In fact, the earlier study by Reever (1984) suggested that the hammer technique would yield better reproducibility over the

Table 8. Summary of Piston and Ballistic Data

Identification No.	Max Chamber Pressure, MPa	Projectile Velocity, m/s	Piston Velocity During Igniter Venting, m/s	Piston Velocity Maximum, m/s
Test Series 1				
9	155	848	2.86	15.04
22	139	847	—	—
23	150	868	—	—
24	155	845	4.33	15.83
25	175	865	3.43	15.92
Mean	155	855		
Std Deviation	13.0 (18.4%)	11.0 (1.0%)		
Test Series 2				
56	188	917	2.42	15.48
57	160	880	2.71	15.20
58	196	918	2.88	14.30
59	156	891	hang fire	
61	175	909	2.10	13.40
Mean	175	903		
Std Deviation	17.3 (9.9%)	16.8 (1.9%)		

Note: The propellant was 1846. All tests in Series 1 and 2 were performed at the one-third propellant charge or 80 cm^3.

Table 9. Summary of Start-up Characteristics

Identification No.	Igniter Charge	P1, MPa	P2, MPa	P_{Ign}, MPa	Time Between P1 and P2, ms
Test Series 1					
9	3.0			10.0	
22	3.0			13.5	
23	3.0			17.5	
24	3.0			27.8	
25	3.0			23.5	
Test Series 2					
56	3.5			19.8	
57	3.5	12.8	28.3	22.2	1.7
58	3.5	5.5		22.0	
59	3.5	5.1	32.2		0.84 (hang fire)
61	3.5	9.0	26.8	15.1	2.7

Table 10. Comparison in Ballistic Performance Between Two Methods for Seating the Projectile

Identification No.	Projectile Seating Method	Chamber Pressure (Maximum), MPa	Muzzle Velocity, m/s
Test Series 3			
68	hammer	131	857
70	hammer	161	888
71	pressed	122	887
72	pressed	127	852
73	pressed	—	853
Mean		135	867
Std Deviation		17.6 (13.0%)	18.4 (2.1%)
Test Series 4			
74	pressed	115	870
75	pressed	113	865
76	pressed	115	870
78	pressed	125	881
79	pressed	126	881
Mean		119	873
Std Deviation		6.2 (5.2%)	7.23 (0.83%)

pressed screw approach. Based on the results of Test Series 3, it was decided to conduct a new series of tests using the pressed screw approach to determine if this was indeed true.

The results from Test Series 4 indicated that the pressed screw technique yielded better reproducibility than the earlier hammer technique. The results showed almost a factor of two improvement over previous test series at the one-third charge. Also, the improved level of reproducibility, demonstrated in Test Group 4, suggests the importance of reproducing the initial conditions for achieving repeatable muzzle velocity. Specifically, the data, although limited to five tests, strongly suggest the importance of duplicating the overall assembly procedures.

5. DISCUSSION AND CONCLUSIONS

Prior to the present study, the standard deviation for the tests with the BRL 30-mm RLPG, Concept VI, was typically about 1.5%. Using the pressed-screw-projectile seating technique and by paying close attention to reproducing the initial conditions, such as orientation of the assembly components and the lubrication procedures, the standard deviation was decreased to 0.8% for a five-round group.

It was found that none of the early start-up parameters that were studied could account for the observed variations in the muzzle velocity. The initial conditions having the most effect on the muzzle velocity reproducibility also were not identified. It would seem, however, that some of the parameters affecting the early projectile motion might play a key role in achieving reproducible muzzle velocity. These parameters include the projectile design, the amount of erosion in the gun tube, and the method for seating the projectile. Of lesser importance, but parameters which should not be overlooked, include the orientation of the piston in the chamber and the volume of lubrication which is used on the piston, parameters which might help to insure similar resistive profiles for the piston displacement.

It should be pointed out that all of the tests with the 30-mm reported here were performed with a reduced injection sheet thickness. For this reason, the muzzle velocities were lower than those which would have been obtained with an optimized injection profile. It is not known if a larger sheet thickness would have contributed to a more consistent muzzle velocity.

The effect of the maximum igniter output pressure was one parameter, which could be examined using an interior ballistic code. The model developed by Coffee (1985) was used. This is a lumped parameter model which specifies a maximum ignition pressure as an input to the model. Details of the igniter venting process are not simulated in the model. Four computer runs were made with the igniter output pressure varying from 12 to 25 MPa. The results of the igniter parametric sensitivity analysis show a decrease in the calculated maximum chamber pressure with an increase in igniter pressure, an unexpected result. A higher igniter pressure displaces the piston faster and moves the projectile earlier, resulting in a larger instantaneous volume, which may account for the predicted lower maximum chamber pressure.

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